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SOLDER MATERIALS WITH MICRO AND NANOPARTICLES: A REVIEW

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EU legislation requires that lead and other critical alloying elements have to be removed or replaced by non-hazardous element in the certain segments of the soldering technology. The mechanical and thermal properties, such as tensile strength and melting point, of the newly developed lead-free solder alloys differsignificantly from the previously used lead-tin solders. Nowadays researchers deal with nanostructured solders that are capable of changing these properties.

The melting point of the solder can be reduced by paste solder from metal nanoparticles and the mechanical properties can be improved by a non-soluble nanoparticle-reinforced nanocomposite solder. The results of research on nanostructured solders are collected in this review.
Keywords: lead-free solder, composite, nanoparticles

Introduction

Till now the most successful solder alloysweretin-lead(Sn-Pb), which has appropriate chemical, physical and thermal properties. These properties result in a good bond between the solder and substrate [1].

Different alloying elements can be used to improve the mechanical properties of lead-free solder, i.e. silver [2] or nickel [3]. Nickel can improve the mechanical properties by reducing the thickness of the Cu_3Sn intermetallic (IMC) layer on the interface of the solder/substrate [3]. The wettability of the solder can be improved by adding rare earth metals, e.g. lanthanum (La) and cerium (Ce) [4].

A higher number of elements in lead-free solder can solve the problem of the melting temperature as well. Namely, the solder materials of highest importance in practice, the SAC alloys (S = tin, A = silver, C = copper) have a higher melting point than the Sn-Pb solders. From the viewpoint of technology,this means that the currently used Printed Circuit Boards (PCBs) must be exchanged for higher temperature tolerant PCBs, which involves higher costs. Solder pastes from nano-sized alloy particles are a promising technique for decreasing the melting point of the solder [5].

Nanoparticles (NPs) are also adapted to improve the mechanical properties, as reinforcing materials. Nowadays, composite materials are widely used for improving the properties of materials. Based on this, we can assume that composites are able to fulfil an important role in soldering technology.

1. Classes of particles for composite solder materials

Nano- and micro-sized particles or fibres are applicablefor the preparation of the composite solder. These reinforcing phases can be metals, oxide-, carbide- or nitride ceramics or non-metals,e.g. carbon nanotubes (CNTs). The reinforcing materials can be classified into the following groups according to their behaviour with the solder material [6, 7]:

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- In Group I we can categorise the nano- and micro-sized solid phases whose particles may react with a component of the solder and can dissolve in the matrix during the melting or reflow to create an IMC on the solder/substrate interface.On this basis, the elements belonging here are Al, Fe, Zn, Ni, Ag, Cu and Co. These elements may be used as micro-sized particles. In this case, due to the larger size of the particles they cannot completely dissolve in the solder materials, and a "flower-like" IMC structure can form on the surface of these micro-sized particles. The properties of the micro-sized-particle reinforced composite solder tend to deteriorate because of the flower-like structure, which can cause cracks.
  The solder material can be composed of nano-sized particles, namely the solder particles are dispersed in an organic medium. This solder material is the paste. Without oxide or any other reinforcing material in this paste it is not a composite solder.

- In Group II the nano-sized intermetallic phases are categorised, e.g. Sn_6Cu_5, Cu_3Sn, Ni_3Sn_4 and Ag_3Sn. The equilibrium can be reached by using these particles and thus the reactivity between the solder and the substratecan be reduced. In this case the melted solder is not able to create a crater in the substrate in contrast with the solder without intermetallic nanoparticles.

- The inert nano- and micro-particles belong to Group III, e.g. Al_2O_3, TiO_2 and CNTs. These particles do not react with the solder material but they are suited for acting as the sites for the heterogeneous nucleation of β-tin or intermetallic phase, so the size of β-tin and IMC can be reduced significantly on the interface of the solder/substrate.
  In the development of a composite solder, similarly to other metal matrix composites [8, 9]. It is necessary to consider that the surface of the reinforcing materials is not wetted perfectly by the melted alloys, which means the adhesion between solder and reinforcing phaseis weak. The adhesion can be improved by a metallic coating on the surface of the reinforcing materials, e.g. nickel coating on the surface of CNTs [10].

2. Preparation of the composite solders

The metal matrix composites can be categorised according to the preparation of the reinforcing materials. Accordingly we can speak about ex-situ and in-situ composites [11].

2.1. Ex-situ composites

Inert reinforcing particles can be mixed or stirred with the melted solder material. In this casting method the melted solder should be prevented from oxidation by using an inert gas atmosphere [12].

Solder paste can be made with reactive reinforcing materials that can react with the solder or can dissolve in the alloy. In this case we can prepare solder paste from the particles of the components.In preparing the solder paste, the reactive particles can be dispersed with the solder powder in a special water or organic solvent soluble flux [12–14].

Bulk solder (stripor wire) can be prepared by a method to avoid chemical reaction between the solder and the reinforcing particles before the soldering. First, the reinforcing particles and the powder of the solder alloy are homogenously mixed in alcohol. After the

drying of this slurry, the desired solder stripor wirecan be prepared bycold forming methods.

2.2. In-situ composites

Recently, the development of in-situ composites has been investigated by several research groups [12, 15–17]. The reinforcing materials are prepared by the reaction between the elements of the solder alloy, e.g. Cu_6Sn_5 phase from the reaction of Sn and Cu. The required elements of the solder are melted and kept at a given temperature for the formation of the desired IMCphase in the alloy, then the alloy is cooled down and hot rolled. In this way the IMCphases will be micro-sized and well dispersed [12, 15].

3. Application of metal nanoparticles

There are two main groups of metal nanoparticles according to their behaviour with the solder material. In the first group we can find the metallic particles that are dissolved in solders such as Ag or Cu. The non-soluble metal particles (e.g. Mo) belong to the other group.

The most commonly used nano- or micro-sized particles for the developing of the solders are from Cu [18], Ag [19], Al [20], Zn [21], Mo [22, 23], Co [24, 25], Ni [26] andSb [27]. These particles have been used for the production of Sn-Ag based solder, e.g. Sn-3.5Ag, and different SAC alloys, as well as for Sn-Pd, Sn-Cu and Sn-Zn alloys [7].

3.1. Interfacial behaviour of the solders containing metal nano- and micro-particles

The wettability of the copper plate can be improved by copper, nickel, or silver nanoparticles containing lead-free solders [6]; similarly, the solders which contain these elements as alloys but not nanoparticles [28].

Mo nanoparticles in Sn-Ag-Cu solder remain stable during multiple reflow cycles at 250 °C and the Mo nanoparticles do not dissolve in the matrix [23]. The molybdenum nanoparticles affect the formation of the IMCphase on the solder/substrate interface. The addition of Mo NPs to solder causes a decreasein the thickness of the IMC layer on the interface.

The effect of the Mo NPs and the insoluble NPswas explained by Haseeb [23], based on a study by Kim and Tu (cited in [23]). There are two IMC layers on the solder/substrate interface in the SAC solder/Cu substrate system. There is a Cu_3Sn IMClayer on the Cu side. The Cu_3Sn layer is covered by an IMClayer of Cu_6Sn_5 scallops which is directly on the solder side. Fluid channels exist between the Cu_6Sn_5 scallops, and these channels are extended to the Cu_3Sn/Cu interface. The fluid channels allow the possibility of quick diffusion for the dissolved copper, which results in further reaction and the extra Cu creates a thicker IMC layer on the interface. In the composite solder the non-soluble NPscan block the fluid channels, because the NPsare sorbed on the surface of the IMC.

The visible contact angle of the solder is increased and the spreading rate is decreased by the addition of non-soluble NPs or fibres to the solder, as shown in Table 1. The viscosity of the solder is increased by adding non-soluble NPs [29]. The higher viscosity keeps the solder from the spreading that gives rise to the increasing of the contact angle [30]. The increased contact angle value, however, is in the $20° \leq \Theta \leq 40°$ range, which is the necessary contact angle range for soldering.

Table 1

Wetting angle and spreading rate of SAC on Cu substrate with various addition of Co NPs [29]

Solder	**Wetting angle(Θ), °**	**Spreading rate,%**
Sn-3.8Ag-0.7Cu	19.46 ± 4.34	82.48 ± 2.42
Sn-3.8Ag-0.7Cu-0.18-CoNPs	26.95 ± 1.02	74.12 ± 4.85
Sn-3.8Ag-0.7Cu-0.41-CoNPs	25.76 ± 1.47	73.40 ± 5.32
Sn-3.8Ag-0.7Cu-0.75-CoNPs	26.71 ± 1.17	60.86 ± 5.32

The metal NPsare important for preparing the composite solder, but the solder itself can be made using metal NPs. In this case, the solderNPsare mixed with solder flux and/or other organic components [31]. Solder pastes prepared with metal NPshave a lower melting point than bulk solder with the same composition [5, 32–37] these results show a good agreement with thetheoretical model as well [35, 36].

The behaviour of the melting point of the SACalloy as a function of particle size was investigated by Gao et al. [32]. In their work an SAC alloy with grain size between 15–60 nm was produced and its melting behaviour was investigated by calorimetry. The melting point of the alloy changed from 218 °C to below190 °C, while the particle size changed from micron size to 10 nm [32]. This melting point is equivalent to the melting point of bulk Sn-Pb alloys, which is between 183 °C and 190 °C [38]. Nano-sized solder alloys, which have a higher melting pointin bulk, are applicable for lower temperature soldering. In this way the lower temperature tolerant PCBsdo not have to be changed to higher temperature tolerant PCBs.

3.2. Mechanical properties ofsolder prepared with metallic nanoparticles

In the development of a solder, there is high interest in its mechanical properties, because the solder bond used in equipment is liable to mechanical stress, such as vibrations, or shocks caused by being dropped. The mechanical properties of the metal NPscontaining solder will be illustrated in the following examples. The first example isan Sn-3.5Ag solder containing Co NPs(Sn-3.5Ag-CoNPs). The shear strength of Sn-3.5Ag-CoNPs compared toSn-3.5Ag improves as a function of the amount of the CoNPs. About 0.1 w% Co NPsin the solder causes an improvement in shear strength by ~28%. The shear strength of the Sn-3.5Ag-Co NPs composite solder reaches its maximum value at 0.1 wt.% CoNPs and from ~1.0 w% CoNPs the shear strength begins to decrease significantly: at 2.0 w% CoNPs reaches the value of the matrix material [39].

The silver in Sn-Zn-AgNPs compsite solder improves the mechanical properties as well. The shear strength of a Sn-Zn-AgNPs composite rises as function of the amount of AgNPs. The shear strength of the Sn-Zn alloy decreases with increasing reflow number. The shear strength of Sn-Zn-AgNPs composite solder is independent of the reflow number. The good mechanical properties are due to the formation of spherical-shaped $AgZn_3$IMCphases that are small in diameter, which can agglomerate and create micrometer-sized $AgZn_3$ islands in the solder [40].

The mechanical properties of Sn-3.5Ag solder can be improved by Ni and Mo nanoparticles. An increase in the amount of MoNPs causes higher hardness; moreover, the addition of Mo NPs and NiNPs can also improve the resistance against creep [41].

4. Application of oxide- and carbide ceramics and non-metallic materials

In the development of composite solders not only metal NPs are used; ceramic or non-metallic nano-sized phasescan also be used as reinforcing phase. The non-metallic reinforcing particles can be composed of oxides, e.g. TiO_2 [42, 43, 44], Al_2O_3 [45, 46], ZrO_2 [47] or Fe-Ni-oxide [48]; carbides, such as the most commonly used SiC [49, 50]; borides, e.g. TiB_2 [30]; as well as nanostructured POSS (polyhedral oligomeric Silsesquioxane) [51] orCNTs and fibres [10, 52, 53]. These materials are applied in order to improve mechanical properties, e.g. hardness and tensile strength, as well as shear strength.

4.1. Wettability and interfacial properties of ceramic NP reinforced compositessolder

The ceramics and non-metallic reinforcing phases can be classified into two groups. Inert materials (e.g. Al_2O_3, TiO_2) belong to the first group; these materials do not react with the components of the solder. Reactive particles, for example SnO_2 [6], belong to the second group. Theseparticles can react or dissolve in the solder. Thus, for the two groups a different effect can be observed in the wetting properties.

The wettability and spreading of the Sn3.5Ag0.7Cu-MWCNT (multi-walled carbon nanotube) and Sn-3.5Ag-0.7Cu-TiB_{2NPs}composite solders were investigated by Nai et al. [30]. They determined that the contact angle decreases as a function of increasing the amount of $TiB_{2\ NPS}$ in the solder. The composite solder can reach the minimum contact angle at 2 vol% $TiB_{2\ NPs}$ content. The viscosity of the solder is increased by a higher amount of $TiB_{2\ NPs}$, so the solder is not able to spread on the surface of the substrate, as seen also in Subsection 3.1 in connection with the CoNPs. This gives a higher contact angle.

The improvement of the wetting of the composite solder was observed with a small amount of other NPs, e.g. TiO_2 (minimum contact angle at 0.1 w% TiO_2[54]), Y_2O_3 (minimum contact angle at 1 w% Y_2O_3[55]) and Al_2O_3 (minimum contact angle at 0.5 w% Al_2O_3[56]).

4.2. The mechanical properties of solder-ceramic NP composites

Ceramic NPs, similar to metal particles, improve the mechanical properties of the composite solders. Gain et al. [47] observed that 0.5 w% ZrO_2 NPs can significantly improve the shear strength compared to solder without NPs. In addition, the reflow number causes only a small decline in the shear strength if the solder consists ofNPs compared to the solder without NPs. We can say from the data in Table 2 that the tensile strength of the composite solder is increased and its ductility is decreased by the addition of oxide NPsor CNTs.

Table 2

Mechanical properties of nanocomposite-SAC solder [57, 58]

Solder	**Reinforcing phase**	**Mechanical properties**	
		Tensile strength, R_m, MPa	**Elongation, %**
Sn3.0Ag0.5Cu	0.00 w%TiO_2	40.90	47.60
	0.25 w%TiO_2	45.80	46.10
	0.50 w%TiO_2	49.10	44.30
	0.75 w%TiO_2	53.00	41.40
	1.00 w%TiO_2	57.00	38.40
	1.25 w%TiO_2	56.00	33.70

Sn3.5Ag0.5Cu	0.00 w%Al_2O_3	54.30	49.20
	0.25 w% Al_2O_3	60.20	47.30
	0.50 w% Al_2O_3	62.40	44.00
	1.00 w% Al_2O_3	68.05	43.50
	1.50 w% Al_2O_3	70.05	32.50
Sn3.8Ag0.7Cu	0.00 w% SWCNT*	37.70	33.30
	0.01 w% SWCNT	40.90	32.70
	0.08 w% SWCNT	44.28	27.32
	0.10 w% SWCNT	48.60	26.57
	0.80 w% SWCNT	53.47	23.28
	1.00 w% SWCNT	56.70	24.36

*SWCNT: single-walled carbon nanotube

Summary

In accordance with European Union legislation lead and other critical alloying elements have to be removed and replaced by non-hazardous elements in the certain segments of the soldering technology. In the interest of achieving the mechanical and thermal properties of the tin-lead alloy, it isnecessary to use two, three or even more alloying elements in the newly developed lead-freesolder.

Several lead-free solders have a higher melting point than the melting temperature of the Sn-Pb alloys. The higher soldering temperature required achange in PCB from lower temperature to higher temperature resistant PCBs. This industrial problem (the change of the PCB) can be solved by using a solder paste made from metal NPs. Solder pastes from nano-sized alloy particles have a lower melting point than the bulk solder with same composition, and their temperature is equivalent to the melting point of the Sn-Pb alloys.

In the development of the solder, its mechanical properties are important because equipment with solder bondingis liable to mechanical stress, such as vibration, or shock caused by falling. The mechanical properties, hardness, tensile strength and shear strength can be improved by adding non-reactive NPs, e.g. Al_2O_3. Moreover, the presence of NPs in solder may decrease the IMClayer thickness on the solder/substrate interface.

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References

[1] LOOMANS, M. E.–VAYNMAN, S.–GHOSH, G.–FINE, M. E.: *J Electron Mater,* 23, 1994, 741–746.

[2] MOLNÁR A.–KARDOS I.–MOLNÁR I.–GÁCSI Z.: *BKL. Kohászat,* 147, 2, 2014, 17–20 (in Hungarian).

[3] YOON, J.-W.–NOH, B.-I.–KIM, B.-K.–SHUR, C.-C.–JUNG, S.-B.: *J Alloy Compd,* 486, 1–2, 2009, 142–147.

[4] WANG, L.–YU, D. Q.–ZHAO, J.–HUANG, M. L.: *Mater Lett,* 56, 2002, 1039–1042.

[5] BAO, T. T.–KIM, Y.–LEE, J.–LEE, J. G.: *Mater Trans,* 51, 2010, 2145–2149.

[6] ZHANG, L.–TU, K. N.: *Mat Sci Eng R,* 82, 2014, 1–32.

[7] CHEN, S.: *Thesis for the degree of licentiate of engineering*. Chalmers Univeristy of Technology, Göteborg, Sweden, 2013.

[8] BAUMLI, P.–SYTCHEV, J.–KAPTAY, Gy.: *J Mater Sci,* 45, 2010, 5177–5190.

[9] BAUMLI, P.–SYCHEV, J.–BUDAI, I.–SZABO, J. T.–KAPTAY, Gy.: *Composites A,* 44, 2013, 47–50.

[10] HAN, Y. D.–NAI, S. M. L.–JING, H. Y.–XU, L. Y.–TAN, C. M.–WEI, J.: *J Mater Sci Mater Electron,* 22 (3), 2011, 315–322.

[11] LEKATOU, A.–KARANTZALIS, E.–EVANGELOU, A.–GOUSIA, V.–KAPTAY, Gy.–GACSI, Z.–BAUMLI, P.–SIMON, A.: *Mater Des,* 65, 2015 1121–1135.

[12] SHEN, J.–CHAN–Y. C.: *Microelectron Reliab,* 49, 2009, 223–234.

[13] LIU, J. P.–GUO, F.–YAN, Y. F.–WANG, W. B.–SHI, Y. W.: *J Electron Mater,* 33 (9), 2004, 958–963.

[14] SHI, Y.–LIU, J.–YAN, Y.–XIA, Z.–LEI, Y.–GUO, F.–LI, X.: *J Electron Mater,* 37 (4), 2008, 507–514.

[15] HWANG, S.-Y.–LEE, J.-W.–LEE, Z.-H.: *J Electron Mater,* 31 (11), 2002, 1304–1308.

[16] KAO, S.-T.–LIN, Y.-C.–DUH, J.-G.: *J Electron Mater,* 35 (3), 2006, 486–493.

[17] SHEN, J.–LIU, Y. C.–GAO, H. X.: *J Mater Sci-Mater El,* 18 (4), 2007, 463–468.

[18] LIN, D.–WANG, G. X.–SRIVATSAN, T. S.–AL-HAJRI, MESLET–PETRAROLI, M.: *Mater Lett,* 53, 2002, 333–338.

[19] TAI, F.–GUO, F.–XIA, Z.-D.–LEI, Y.-P.–SHI, Y.-W.: *Int J Min Met,* 16 (6), 2009, 677–684.

[20] GAIN, A. KUMAR–FOUZDER, T.–CHAN, Y. C.–SHARIF, A.–WONG, N. B.–YUNG, Winco K. C.: *J Alloy Compd,* 506, 2010, 216–223.

[21] HASEEB, A. S. M. A.–LEONG, Y. M.–ARAFAT, M. M.: *Intermetallics,* 54, 2014, 86–94.

[22] ARAFAT, M. M.–HASEEB, A. S. M. A.–JOHAN, M. R.: *Solder Surf Mt Tech,* 23 (3), 2011, 140–149.

[23] HASEEB, A. S. M. A.–ARAFAT, M. M.–JOHAN, M. R.: *Mater Charact,* 64, 2012, 27–35.

[24] HASEEB, A. S. M. A.–LENG, T. S.: *Intermetallics,* 19, 2011, 707–712.

[25] LEE, J.-S.–CHU, K.-M.–JEON, D. Y.–PATZELT, R.–MANESSIS, D.–OSTMANN, A.: Electronic Components and Technology Conference. *Proceedings,* 2006, DOI: 10.1109/ECTC.2006.1645654

[26] TAY, S. L.–HASEEB, A. S. M. A.–JOHAN, M. R.–MUNROE, P. R.–QUADIR, M. Z.: *Intermetallics,* 33, 2013, 8–15.

[27] SHAFIQ, I.–CHAN, Y. C.–WONG, N. B.–YUNG, W. K. C.: *J Mater Sci-Mater El,* 23 (7), 2012, 1427–1434.

[28] BAUMLI P.–VASKÓ G.–LACZKÓ S.–SYTCHEVA A.–SVÉDA M.: *BKL. Kohászat,* 147 (2), 2014, 21–25 (in Hungarian).

[29] TAY, S. L.–HASEEB, A. S. M. A.–JOHAN, Mohd Rafie: *Solder Surf Mt Tech,* 23 (1), 2011, 10–14.

[30] NAI, S. M. L.–WEI, J.–GUPTA, M.: *Thin Solid Films,* 504 (1–2), 2006, 401–404.

[31] JIANG, H.–MOON, K.-S.–HUA, F.–WONG, C. P.: *Chem Mater,* 19 (18), 2007, 4482–4485.

[32] JIANG, H.–MOON, K.-S.–HUA, F.–WONG, C. P.: Electronic Components and Technology Conference. *Proceedings 57th*, 2007, 54–58. DOI: 10.1109/ECTC.2007.373776; ISSN: 0569-5503
[33] GAO, Y.–ZOU, C.–YANG, B.–ZHAI, Q.–LIU, J.–ZHURAVLEV, E.–SCHICK, C.: *J Alloys Compd,* 484, 2009, 777–781.
[34] ZOU, C.-D.–GAO, Y.–YANG, B.–ZHAI, Q.: *Trans. Nonferrous Met. Soc. China,* 20, 2010, 248−253.
[35] KAPTAY, Gy.: *J Mater Sci,* 47, 2012, 8320–8335.
[36] KAPTAY, Gy.–JANCZAK-RUSCH, J.–PIGOZZI, G.–JEURGENS, L. P. H.: *J Mater Eng Perform,* 23, 2014, 1600–1607.
[37] ZOU, C.-D.–GAO, Y.–YANG, B.–ZHAI, Q: *Mater Charact,* 61, 2010, 474–480.
[38] ABTEW, M.–SELVADURAY, G.: *Mat Sci Eng: R: Reports,* 27 (5–6), 2000, 95–141.
[39] LEE, J.-S.–CHU, K.-M.–PATZELT, R.–MANESSIS, D.–OSTMANN, A.–JEON, D. Y.: *Microelectron Eng,* 85, 2008, 1577–1583.
[40] GAIN, A. K.–CHAN, Y. C.–SHARIF, A.–WONG, N. B.–YUNG, W. K. C.: *Microelectron Reliab,* 49, 2009, 746–753.
[41] NIRANJANI, V. L.–RAO, B. S. S. Chandra–SARKAR, Rajdeep–KAMAT, S. V.: *J Alloy Compd,* 542, 2012, 136–141.
[42] LIN, D. C.–LIU, S.–GUO, T. M.–WANG, G. X.–SRIVATSAN, T. S.–PETRAROLI, M.: *MaterSci Eng A,* 360, 2003, 285–292.
[43] GAIN, A. K.–CHAN, Y. C.–YUNG, W. K. C.: *Microelectron Reliab,* 51, 2011, 975–984.
[44] CHANGS. Y.–JAIN, C. C.–CHUANG, T. H.–FENG, L. P.–TSAO, L. C.: *Mater Design,* 32, 2011, 4720–4727.
[45] CHUANG, T. H.–WU, M. W.–CHANG, S. Y.–PING, S. F.–TSAO, L. C.: *J Mater Sci-Mater El,* 22 (8), 2011, 1021–1027.
[46] CHANG, S. Y.–TSAO, L. C.–WU, M. W.–CHEN, C. W.: *J Mater Sci-Mater El,* 23 (1), 2012, 100–107.
[47] GAIN, A. K.–CHAN, Y. C.–YUNG, W. K. C.: *Microelectron Reliab,* 51, 2011, 2306–2313.
[48] CHELLVARAJOO, S.–ABDULLAH, M. Z.–SAMSUDIN, Z.: *Mater Design,* 67, 2015, 197–208.
[49] EL-DALY, A. A.–AL-GANAINY, G. S.–FAWZY, A.–YOUNIS, M. J.: *Mater Design,* 55, 2014, 837–845.
[50] LIU, P.–YAO, P.–LIU, J.: *J Electron Mater,* 37 (6), 2008, 874–879.
[51] SHEN, J.–PENG, C.–YIN, H. G.–CHEN, J.: *J Mater Sci-Mater El,* 23 (9), 2012, 1640–1646.
[52] BUKAT, K.–SITEK, J.–KOSCIELSKI, M.–JAKUBOWSKA, M.–SLOMA, M.–MLOZNIAK, A.–NIEDZWIEDZ, W.: *Solder Surf Mt Tech,* 24 (4), 2012, 267–279.
[53] HE, P.–LÜ, X.-C.–LIN, T.-S.–LI, H.-X.–An, J.–MA, X.–FENG, J.-C.–ZHANG, Y.–LI, Q.–QIAN, Y.-Y.: *Trans Nonferrous Met Soc China,* 22, 2012, 692−696.
[54] TANG, Y.–PAN, Y. C.–LI, G. Y.: *J Mater Sci-Mater El,* 24 (5), 2013, 1587–1594.
[55] LIU, X. Y.–HUANG, M. L.–WU, C. M. L.–WANG, L.: *J Mater Sci-Mater El,* 21 (10), 2010, 1046–1054.
[56] TSAO, L. C.–CHANG, S. Y.–LEE, C. I.–SUN, W. H.–HUANG, C. H.: *Mater Design,* 31 (10), 2010, 4831–4835.
[57] FU, S.-M.: *Master Thesis.* China, 2012.
[58] TSAO, L. C.: *Corrosion Resistance.* Book chapter. 2012, 107–132.